

# Rheology of the Mantle

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There have been two main avenues of investigation of the rheology of the mantle: theoretical and laboratory studies of the mechanical behavior of solids and direct estimates obtained by comparing geologic observations with model calculations in which rheological parameters are the principal variables. Studies of large-scale mantle flow, such as convection, might also put some constraints on mantle rheology, although at the present better knowledge of the rheology is needed to specify suitable models for investigation.

The main advances of the last 4 years in our understanding of mantle rheology have been in the realization that the lower mantle may be less resistant to creep than was previously believed and in the realization and preliminary investigation of the complexities of the convection problem.

## Theoretical and Laboratory Studies

Such studies have related creep in crystalline materials at high temperature to the diffusion rates of the atomic species found in the material and have confirmed that mantle material will creep at low stress levels [Gordon, 1967; Sherby and Burke, 1967; McKenzie, 1968a; Weertman, 1970]. Thus creep is a thermally activated process, like seismic-wave attenuation [Gordon, 1967], and, although different mechanisms may be responsible for the two phenomena, studies of one may shed light on the conditions in the mantle that affect both processes [Anderson and O'Connell, 1967; Jackson and Anderson, 1970].

Gordon [1967] and McKenzie [1968a] have considered Nabarro-Herring creep as the controlling mechanism in the mantle. This gives a linear stress-strain rate relation and defines a Newtonian viscosity  $\eta$  that varies as the atomic diffusion coefficient. When applied to the mantle, the resulting model consists of a very high-viscosity lithosphere ( $\eta \lesssim 10^{27}$  poises)  $\sim 100$  km thick, a low-viscosity ( $\eta \sim 10^{21}$  poises) upper mantle  $\sim 500$  km thick, and a rapid rise in viscosity throughout the lower mantle, reaching  $\sim 10^{27}$  poises at the base of the mantle. The low-viscosity region results from the rapid increase of temperature with depth in the upper mantle, whereas in the lower mantle the effect of pressure predominates and raises the viscosity. The main picture from this model is thus a low-viscosity upper mantle ( $\eta \sim 10^{21}$ ) to a depth of  $\sim 500$  km and a high-viscosity lower mantle ( $\eta \lesssim 10^{26}$ ) below a 1000-km depth.

Gordon [1967] and Weertman [1970] have pointed out that Nabarro-Herring creep applies to material with roughly equant grain shape and leads to elongation of

the individual grains. For large strains the grains would become so distorted that recrystallization might become energetically favorable, and grain boundary migration and dislocation movement, rather than vacancy diffusion, would be the rate controlling process.

Weertman [1970] has discussed the condition when creep is controlled by the movement of dislocations, which would be the case for stresses greater than  $\sim 10^{-2}$  bar for mantle material. (For smaller stresses Nabarro-Herring creep would dominate.) For this mechanism the strain rate  $\dot{\epsilon}$  depends on some power  $n$  of the stress  $\sigma$ , with  $n$  commonly between 3 and 6. In spite of the nonlinearity of this relation, one can define an effective viscosity  $\eta \equiv \sigma/\dot{\epsilon}$  that will depend on the strain rate (or stress) as well as temperature and pressure. As strain rate or stress increases, the effective viscosity decreases, rather than remains constant as for Nabarro-Herring creep. Applying these considerations to the mantle for a creep rate of  $10^{-16} \text{ sec}^{-1}$ , Weertman finds that the effective viscosity of the lower mantle increases much more slowly with depth than is implied by Nabarro-Herring creep, and reaches only  $\sim 10^{23}$  poises at the base of the mantle, where the corresponding stress would be  $\sim 30$  bars. In the upper mantle this mechanism predicts a low-viscosity region similar to that implied by Nabarro-Herring creep.

Experimental studies relevant to creep in the mantle have been discussed by the authors cited above. The main difficulties are in performing creep experiments under a high enough pressure to avoid grain boundary sliding or the creation of voids or excess vacancies and in ensuring that the conditions of steady-state, rather than transient, creep are attained. To attain a strain of  $\epsilon \sim 1$  at a rate of  $10^{-15} \text{ sec}^{-1}$  would require 30 m.y.; yet this is a short time geologically.

In the upper mantle the flow properties may be more complex than is implied by theories of creep in solids. Anderson and Sammis [1970] have discussed the considerations that lead them to conclude that the seismic low-velocity zone contains small ( $\sim 1\%$ ) amounts of melt. The exact rheology of such a partially molten region is not known, although such a region would most probably have a low effective viscosity [Weertman, 1970].

## Direct Estimates of Mantle Rheology

These estimates have primarily come from consideration of the isostatic rebound of the earth's surface following the removal of a surface load, such as an ice sheet. McConnell [1968a, b] has deduced a relaxation time spectrum for the uplift of Fennoscandia that gives a characteristic relaxation time for each Fourier component of the surface deformation. (On a sphere the spectrum is discrete and relates relaxation time to spherical harmonic degree.) Comparing this spectrum with that calculated for a layered Newtonian viscous half-space overlain by an elastic lithosphere, he infers a low-viscosity region ( $\eta \sim 10^{21}$  poises) between 200 and 400 km with the viscosity increasing to  $10^{23}$  at the 1200-km depth. This interpretation is in agreement with

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Crittenden's [1967] value of  $10^{20}$ – $10^{21}$  poises under Lake Bonneville, obtained from a uniform half-space model. Similar studies of the response of the crust and upper mantle to loads have been done by Walcott [1970] and Brothie and Sylvester [1969], and Andrews [1970] has discussed the response of the earth to a retreating ice sheet.

Because of the limited areal extent of areas like Fennoscandia, the uplift in these areas is determined primarily by the properties of the upper mantle; larger-scale deformations must be studied to investigate the rheology of the lower mantle [McConnell, 1968b; O'Connell, 1969, 1971].

MacDonald [1963] and McKenzie [1967a] had derived a viscosity for the lower mantle of  $\sim 10^{26}$ – $10^{27}$  poises by assuming that the earth's nonhydrostatic bulge is due to the delayed readjustment of the earth's shape to a slowing rate of rotation. This assumption rested on their belief that the bulge was anomalously larger than other departures of the earth's shape from a hydrostatic one. Goldreich and Toomre [1969], however, showed that the ellipticity of the equator is as large as the bulge and proposed that the bulge was simply a consequence of the earth's rotating about its axis of the greatest moment of inertia. In addition they showed that the rate and pattern of polar wandering inferred from paleomagnetism suggested that the average effective viscosity of the mantle is less than  $10^{24}$  poise.

### Convection and Large-Scale Flow

Recent discussions of large-scale movements and convection in the mantle have been given by Knopoff [1967a, b, 1969] and McKenzie [1968b, 1969]. The previous estimate of the viscosity of the lower mantle of  $\sim 10^{26}$  poises implied that convection might not occur in the lower mantle and led to the investigation of models in which only the upper mantle convected [e.g., Turcotte and Oxburgh, 1967]. The more recent suggestion that the lower mantle effective viscosity is  $\sim 10^{23}$  poises requires that mantle-wide convection be considered as well. Even for large-viscosity differences ( $\sim 10^3$ ) between the upper and lower mantles, Rayleigh convection implies flow in the lower mantle [Takeuchi and Sakata, 1970]. The results of Foster [1969], who included volumetric heat sources in his model of convection, give a similar result.

Because of mathematical difficulties, only models with a linear stress-strain rate have been investigated. The effect of a nonlinear relation needs to be investigated. Progress has been made in the recognition of the possible effects that complicate the modeling of mantle convection. Knopoff [1967b] and Foster [1969] have shown that mantle convection may not be steady state. Busse [1967] has shown that the temperature dependence of material properties can lead to periodic convection. Rice [1970] has shown the large nonlinear effect of viscous heating and volumetric heat sources on the flow rates of a convection model. Schubert and Turcotte [1971] have discussed the effects of phase changes on convection in the mantle. The effects of

lithospheric slabs sinking in the mantle have been discussed by McKenzie [1969], and some model calculations have been done by Turcotte and Oxburgh [1968] and Minear and Toksöz [1970]. The effects of partial melting, mobility of fluid phases, and chemical differentiation on the rheology and flow patterns have yet to be considered in detail. In view of all these complications, much progress is yet to be made on the problem of mantle convection. Yet an understanding of the problem is necessary to understand such phenomena as continental drift, polar wandering, the earth's nonhydrostatic gravity field, the shape of the earth, the core-mantle boundary, interaction between the core and mantle [Hide and Horai, 1968], and the structure and composition of the mantle.

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## Elastic Properties of Minerals

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During the last 4 years research in the elastic properties of minerals has been focused on several major areas: (1) measurement of the pressure and temperature dependence of the elastic properties of the minerals that are primary constituents of earth-forming rocks; (2) measurement of the ambient properties of additional natural minerals and rocks; (3) study of the effect of rock fabric, porosity, and fluid content on the elastic properties of polycrystalline aggregates; (4) development of new experimental techniques to enable measurement at high temperature and at high pressure simultaneously and to measure velocities in natural rocks more precisely; (5) establishment of systematic trends in the data

that lead to the formulation of a semiempirical equation of state relating the zero-pressure elastic properties of minerals. In this brief report, we attempt only to highlight the major advances that have been made in these areas. The reader is referred to the bibliography for further details.

### Measurements of the Elastic Properties of Minerals

**Pressure and Temperature Dependence.** The marked increase of activity in geophysical laboratories has been directed toward the measurement of the elastic properties of minerals as a function of temperature and pressure. The data provide the input parameters for equations of state of solids used to extrapolate the experimental results to higher pressures and temperatures and to compare with the observed properties of the earth's interior. To gain adequate precision for these data, measurements using ultrasonic techniques have been used on specimens of high acoustic quality. There are now at least ten geophysical laboratories in the United States conducting such experiments; in general, the agreement in the results for the various laboratories and specimens is good when care has been exercised to characterize the specimen and to control the experimental conditions.

The bulk of the work to date has been concentrated on materials that are important to geophysical and geochemical theories of the earth's interior: periclase

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